3 Simplified Model Description

This section describes—in simplified form—the variables, constraints, and other attributes in the linear program formulation of ReEDS. It outlines, in order:

1. Subscripts (variables and constraints)
2. Major decision variables
3. The objective function
4. Constraints

A fully detailed listing of the variables and constraints is contained in Appendix A.

3.1 Subscripts

Variables, parameters, and constraints are all subscripted to describe the space over which they apply. The various sets are listed below.

3.1.1 Geographical Sets:

- i, j—356 supply/demand regions track where wind and solar power are generated and to where they are transmitted. Source regions are generally noted 'i' and destinations, 'j.'
- n, p—134 balancing authorities (abbreviated PCA, for Power Control Authority), each of which contains one or more supply/demand regions, track dispatchable generation. Source regions are generally noted 'n' and destinations, 'p.'
- *states*—There are 48 states (no Alaska or Hawaii).
- *rto*—32 regional transmission organizations, each of which contains one or more balancing authorities. In the base case, reserve margin requirements, operating reserve requirements, and wind curtailments are monitored at the RTO level, though there is an option in the code to use balancing areas, NERC regions, or interconnects instead of RTOs.
- r—There are 13 NERC regions/subregions.
- *in*—There are 3 interconnects that are electrically isolated from each other.

3.1.2 Temporal Sets:

- *year*—2006 to 2050
- *period*—There are 23 2-year periods
- s—4 annual seasons
- m—16 time-slices during each year, with four seasons and four daily time-slices in each season plus one superpeak time-slice. (Spring has only 3 slices.)

3.1.3 Other Sets:

- c—5 wind classes
- l—3 wind locations (*onshore, shallow offshore, deep offshore*)
- *cCSP*—5 Concentrated Solar Power (CSP) classes
- *pol*—4 pollutants (SO_2, NO_x, Hg, CO_2)
- q—Conventional generating technologies:
    - hydropower
    - natural gas
      combustion turbine
      combined cycle
      combined cycle with carbon capture and sequestration (CCS)
    - coal
      traditional pulverized coal, unscrubbed, scrubbed, or cofiring
      modern pulverized, with or without cofiring
      integrated gasification combined cycle (IGCC) with or without CCS
    - oil-gas-steam
    - nuclear
    - dedicated biomass
    - geothermal
    - landfill gas/municipal solid waste
    - others
- *st*—There are 3 storage technologies:
    - pumped hydropower (PHS)
    - batteries
    - compressed air energy storage (CAES)

3.2 Major Decision Variables

The major decision variables include capacity of conventionals, renewables, and storage along with transmission; and dispatch of conventional capacity and storage. Unless otherwise noted, capacity variables are expressed in megawatts and energy variables are expressed in megawatt-hours.

- $\mathrm{Wtur}_{c,i,l}$ — new wind capacity
- $\mathrm{WN}_{c,i,j,l}$ — new wind transmission capacity between regions
- $\mathrm{WS}_{n,m}$ — wind curtailments (surplus)
- $\mathrm{CSPtur}_{cCSP,i}$ — new CSP capacity
- $\mathrm{CSPN}_{cCSP,i,j}$ — new CSP transmission capacity
- $\mathrm{CSPS}_{n,m}$ — CSP curtailments (surplus)
- $\mathrm{ReT}_{n,p}$ — new transmission capacity for wind and CSP (renewables) between balancing areas

- $\mathrm{CONV}_{n,q}$ — conventional capacity
- $\mathrm{CONVgen}_{n,m,q}$ — conventional generation
- $\mathrm{SR}_{n,m,q}$ — spinning reserve capacity
- $\mathrm{QS}_{n,q}$ — quickstart capacity
- $\mathrm{CONVT}_{n,p,m}$ — conventional transmission needs
- $\mathrm{STOR}_{n,st}$ — new storage capacity
- $\mathrm{STORin}_{n,m,st}$ — energy into storage
- $\mathrm{STORout}_{n,m,st}$ — energy from storage
- $\mathrm{STOR\_OR}_{n,m,st}$ — storage operating reserve capacity
- $\mathrm{TPCAN}_{n,p}$ — new transmission capacity for dispatchable sources
- $\mathrm{CONTRACTcap}_{n,p}$ — firm capacity contracted from another region
- RPSshortfall

3.3 Objective Function

In the objective function we minimize z where

$$
\begin{aligned}
z \quad = \quad & \sum_{c,i,l} \mathrm{Wtur}_{c,i,l} \cdot \$capacity_l \\
+ \quad & \sum_{c,i,j,l} \mathrm{WN}_{c,i,j,l} \cdot \$capacity_l \\
+ \quad & \sum_{cCSP,i} \mathrm{CSPtur}_{cCSP,i} \cdot \$capacity \\
+ \quad & \sum_{cCSP,i,j} \mathrm{CSPN}_{cCSP,i,j} \cdot \$capacity \\
+ \quad & \sum_{n,q} \mathrm{CONV}_{n,q} \cdot \$capacity_q \\
+ \quad & \sum_{n,p} \mathrm{TPCAN}_{n,p} \cdot \$capacity \\
+ \quad & \sum_{n,m,q} \mathrm{CONVgen}_{n,m,q} \cdot (\$operation_q + \$fuel_q) \\
+ \quad & \sum_{n,m,q} \mathrm{SR}_{n,m,q} \cdot \$operation_q \\
+ \quad & \sum_{n,q} \mathrm{QS}_{n,q} \cdot \$capacity_q \\
+ \quad & \sum_{n,st} \mathrm{STOR}_{n,st} \cdot \$capacity_{st} \\
+ \quad & \sum_{n,m,st} \mathrm{STORout}_{n,m,st} \cdot (\$operation_{st} + \$fuel_{st}) \\
+ \quad & \sum_{n,m,q} \mathrm{CONVgen}_{n,m,q} \cdot \$pollution_q \\
+ \quad & \mathrm{RPSshortfall} \cdot \$penalty
\end{aligned}
$$

3.4 Constraints

The minimization of cost in ReEDS is subject to a large number of different constraints, involving limits on resources, transmission constraints, ancillary services, and pollution, along with requirements to meet capacity and generation needs. Unless specifically noted otherwise (see, for example, the wind resource limit below), these constraints apply to new generating capacity built in the time period being optimized.

The constraint name is shown with the subscripts over which the constraint applies. For example, in the constraint immediately below, the subscript '*c, i, l*' immediately following the name of the constraint implies that this constraint is applied for every class of wind *c*, every region *i*, and every location *l*. Because there are 356 regions, five classes of wind, and three locations, this first type of constraint is repeated 5,340 times (356x5x3). The variables may have the same subscripts, but, for simplicity, the subscripts of the constraint are omitted in the variables.

3.4.1 Constraints on Wind

Wind Resource Constraint: all wind capacity installed must be less than the total wind resource in the region.

$WIND\_RES\_UC_{c,i,l}$

$$\mathrm{Wtur} + \mathit{Wtur\_old} \leq \textit{total wind resource}$$

Wind Transmission Constraint: New wind power transmitted from a region must be less than or equal to the total amount of new wind capacity built in that region.

$WIND\_2\_GRID_{c,i,l}$

$$\sum_j \mathrm{WN}_j \leq \mathrm{Wtur}$$

Wind Curtailments: Wind that can not be absorbed by the load is considered surplus and will be subtracted from wind generation in the load constraint.

$WIND\_DEMAND\_LIMIT_{n,m}$

$$\mathrm{WS} \geq \sum_{c,i,j,l}^{j \in n} \mathrm{WN}_{c,i,j,l} - \mathit{load}$$

3.4.2 Constraints on CSP

CSP Resource Limit: all CSP capacity installed must be less than the total solar resource in the region.

$CSP\_RES\_UC_{cCSP,i}$

$$\mathrm{CSPtur} + \mathit{CSPtur\_old} \leq \textit{total CSP resource}$$

CSP Transmission Constraint: New CSP transmitted from a region must be less than or equal to the total amount of new CSP capacity built in that region.

CSP_2_GRID$_{cCSP,i}$

$$\sum_{j} \mathrm{CSPN}_j \quad \leq \quad \mathrm{CSPtur}$$

CSP Curtailments: CSP that can not be absorbed by the load is considered surplus and will be subtracted from CSP generation in the load constraint.

CSP_DEMAND_LIMIT$_{n,m}$

$$\mathrm{CSPS} \quad \geq \quad \sum_{c,i,j}^{j \in n} \mathrm{CSPN}_{c,i,j} - load$$

3.4.3 General Renewable Constraints

Limits on Existing Transmission: New wind and CSP imported into a region can not exceed the amount of transmission available to transport it.

WIND_interregion_trans$_j$

$$\sum_{c,i,l} \mathrm{WN}_{c,i,l} + \sum_{cCSP,i} \mathrm{CSPN}_{cCSP,i} \quad \leq \quad \sum_{i} available\ transmission\ capacity_i$$

RPS Requirement: Total national annual renewable generation must exceed a specified fraction of the national electricity load or a penalty (defined here, levied in the objective function) must be paid on the shortfall.

RPSConstraint

$$\begin{aligned}
\sum_{c,i,j,l} (\mathrm{WN}_{c,i,j,l} + WN_old_{c,i,j,l}) \cdot CF_{c,i,l} - \sum_{n,m} \mathrm{WS}_{n,m} \quad &+ \\
\sum_{cCSP,i,j} (\mathrm{CSPN}_{st} + CSPN_old_{c,i,j}) \cdot CF_{cCSP} - \sum_{n,m} \mathrm{CSPS}_{n,m} \quad &+ \\
\sum_{n} \mathrm{CONVgen}_{n,geothermal} + \sum_{n} \mathrm{CONVgen}_{n,biopower} \quad &+ \\
\mathrm{RPSshortfall} \quad &\geq \quad \sum_{n,m} load_{n,m} \cdot RPS\,fraction
\end{aligned}$$

A duplicate of this constraint exists at the state level and can be seen in the detailed model description, below. It should be noted that legislated requirements of this type—emissions, RPS, etc.—can be constrained at any of the regional levels contained in the model, though such constraints are not generally included in the current version.

3.4.4 Constraints on System Operation

Generation Requirement: Generation plus net imports plus net storage must meet load requirements in each balancing authority in each time-slice.

LOAD_PCA$_{n,m}$

$$\sum_q \mathrm{CONVgen}_q + \sum_p \mathrm{CONVT}_{n,p,m} \quad +$$

$$\sum_{c,i,j,l}^{j\in n} (\mathrm{WN}_{c,i,j,l} + WN\_old_{c,i,j,l}) \cdot CF_{c,m,l} - \mathrm{WS} \quad +$$

$$\sum_{cCSP,i,j}^{j\in n} (\mathrm{CSPN}_{st} + CSPN\_old_{c,i,j}) \cdot CF_{cCSP,m} - \mathrm{CSPS} \quad +$$

$$\sum_{st} \mathrm{STORout}_{st} \quad \geq \quad load + \sum_p \mathrm{CONVT}_{p,n,m} + \sum_{st} \mathrm{STORin}_{st}$$

Reserve Margin Requirement: Dispatchable capacity plus capacity value of wind and CSP plus storage capacity plus net contracted firm capacity must exceed the peak annual load plus a reserve margin.

RES_MARG$_{rto}$

$$\sum_{n,q}^{n\in rto} \mathrm{CONV}_{n,q} \quad +$$

$$\sum_{c,i,j,l}^{j\in rto} \mathrm{Wtur}_{c,i,j,l} \cdot CV_{c,i,l} \quad +$$

$$\sum_{cCSP,i,j}^{j\in rto} \mathrm{CSPtur}_{cCSP,i,j} \cdot CV_{cCSP,i} \quad +$$

$$\sum_{n,st}^{n\in rto} \mathrm{STOR}_{n,st} \cdot CV_{n,st} \quad +$$

$$\sum_{n,p}^{n\in rto} (\mathrm{CONTRACTcap}_{p,n} - \mathrm{CONTRACTcap}_{n,p}) \quad \geq \quad \sum_{n}^{n\in rto} peak\ load_n \cdot (1 + reserve\ margin_n)$$

Operating Reserve Requirement: Spinning reserve plus quick-start capacity plus storage capacity must meet the normal operating reserve requirement plus that imposed by wind.

OPER_RES$_{rto,m}$

$$\sum_{n,q}^{n\in rto} (\mathrm{SR}_{n,q} + \mathrm{QS}_{n,q}) + \sum_{st} \mathrm{STOR\_OR}_{n,st} \quad \geq \quad \sum_{n}^{n\in rto} normal\ operating\ reserve\ reqt_n + \sum_{c,i,l} wind\text{-}induced\ operating\ reserve\ reqt_{c,i,l}$$

Spinning Reserve Constraint: Spinning reserve available in a given time-slice is limited to a fraction of the peak seasonal output of that plant.

SPIN_RES_CAP$_{n,m,q}$

$$\mathrm{SR} \quad \leq \quad \mathrm{CONVgen}_{seasonpeak} \cdot SR\,fraction_q$$

Capacity Dispatch Constraint: Conventional capacity (after outages) must be sufficient to supply all the firm power, spinning reserve, and quickstart capacity demanded in each time-slice.

CAP_FO_PO$_{n,m,q}$

$$\text{CONVgen} + \text{SR} + \text{QS} \quad \leq \quad \text{CONV} \cdot (1 - \textit{outage rate})$$

Minimum Load Constraint: Conventional plants with minimum load requirements can not operate below the prescribed level.

MIN_LOADING$_{n,m,q}$

$$\text{CONVgen} \quad \geq \quad \text{CONVgen}_{peak} \cdot \textit{minimum load fraction}$$

3.4.5 Constraints on Storage

Energy Balance: Energy discharged from storage must not exceed the energy used to charge storage (after accounting for round-trip efficiency) within a single season.

ENERGY_FROM_STORAGE$_{n,s,st}$

$$\sum_{m}^{m\in s} \text{STORout}_m \quad \leq \quad \sum_{m}^{m\in s} \text{STORin}_m \cdot \textit{round-trip efficiency}$$

Dispatch Constraint: Storage capacity (after outages) must be sufficient to supply all charging power, discharging power, and operating reserve demanded in each time-slice.

STORE_FO_PO$_{n,m,st}$

$$\text{STORout} + \text{STORin} + \text{STOR\_OR} \quad \leq \quad \text{STOR} \cdot (1 - \textit{outage rate})$$

3.4.6 Others

Hydropower Energy Constraint: The energy generated from hydroelectric capacity must conform to the historical availability of water.

HYDRO_ENERGY$_n$

$$\sum_{m} \text{CONVgen}_{m,hydro} \quad \leq \quad \textit{annual hydro energy available}$$

SO_2 Scrubber Constraints: Combined capacity of the scrubbed and unscrubbed coal plants must be equal to the total of the two from the last period minus retirements. Furthermore, unscrubbed coal capacity can not exceed the unscrubbed capacity of the last period minus retirements. This allows the unscrubbed to become scrubbed, i.e., the unscrubbed capacity can decrease but the total can not.

SCRUBBER$_n$

$$\text{CONV}_{scrubbedcoal} + \text{CONV}_{unscrubbedcoal} = CONVold_{scrubbedcoal} + CONVold_{unscrubbedcoal} - retirements$$

-and-

$$\text{CONV}_{unscrubbedcoal} = CONVold_{unscrubbedcoal} - retirements$$

Emissions Constraint: National annual emissions of each pollutant (CO_2, SO_2, NO_x, Hg) by all generators do not exceed their respective national caps.

EMISSIONS$_{pol}$

$$\sum_{n,q} \text{CONVgen}_{n,q} \cdot emissions_q + \sum_{n} \text{STORout}_{n,CAES} \cdot emissions_{CAES} \leq emissions\ \ limits$$

Transmission Constraint: Transmission between balancing authorities must be sufficient to carry all wind, CSP, and conventional energy being sent between those areas.

CONV_TRAN_PCA$_{n,p,m}$

$$\text{TPCAN} \geq \text{ReT} + \text{CONVT}$$